Progress in Nuclear Energy 77 (2014) 266–281

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Status of the very high temperature reactor system

Michael A. Fütterer[a,*], Li Fu[b], Carl Sink[c], Sander de Groot[d], Manuel Pouchon[e], Yong Wan Kim[f], Frank Carré[g], Yukio Tachibana[h]

[a] European Commission, Joint Research Centre – Institute for Energy and Transport, P.O. Box 2, NL-1755 ZG Petten, The Netherlands
[b] INET, Tsinghua University, Beijing 100084, PR China
[c] US Department of Energy, 1000 Independence Ave. SW, Washington, DC 20585, USA
[d] NRG, P.O. Box 25, NL-1755 ZG Petten, The Netherlands
[e] PSI, CH-5232 Villigen, Switzerland
[f] KAERI, 989-111 Daedeokdaero, Yuseong, Daejeon 305-353, Republic of Korea
[g] CEA, DEN, F-91191 Gif-sur-Yvette Cedex, France
[h] JAEA, Oarai, Ibaraki 311-1393, Japan

A R T I C L E I N F O

Article history:
Received 9 December 2013
Received in revised form
14 January 2014
Accepted 21 January 2014
Available online 14 February 2014

Keywords:
Generation IV international forum
Very high temperature reactor
Materials
Fuel
Hydrogen production
International cooperation

A B S T R A C T

The purpose of this paper is to provide an update on the international effort in the development of the Very High Temperature Reactor system pursued through international collaboration in the Generation IV International Forum (GIF) and an outlook for further activities.

The initial motivations to develop this reactor type are recalled, a historical overview is given about technology developments and test reactors since 1945 and several of the targeted non-electric applications of VHTR power are addressed.

Cooperation in the frame of GIF is clearly beneficial for all project partners. Initially, a wealth of historical experience was collected and shared in the form of documents, dedicated workshops or fuel and material samples. This exchange included properties data, fabrication, irradiation and post-irradiation testing methods, quality assurance, design and analysis tools and methods, as well as the experience in building and operating related equipment. In the further course of the project execution, time, effort and scarce facilities (such as irradiation space or hot cell equipment) are shared, they accelerate progress and create synergies.

Recent highlights from currently active GIF VHTR R&D projects (Materials, Fuel and Fuel Cycle, Hydrogen Production) are then provided and placed into the context of the GIF VHTR signatories' national programs. The majority of these currently focus on licensing requirements for demonstrators of near term process steam production scenarios while more aggressive, longer term and higher temperature applications are mainly pursued to enable thermochemical production of bulk hydrogen.

Based on the VHTR's high technology readiness level, orientations for future R&D are outlined which would contribute to enhancing the system's market readiness level. These include work on System Integration and Assessment, Safety Analysis and Demonstration, Waste Minimization and Cost Reductions.

The inherent safety characteristics of the VHTR are a precious asset for it to become a strong response to today's concerns of nuclear safety, energy security and climate change.

1. Introduction

Fast population growth globally, industrialization of emerging countries and political instabilities have confronted the world already for several decades with ever increasing energy challenges. Despite tremendous efforts to cut back on the use of fossil fuel, most of the growing energy demand is still being satisfied with fossil hydrocarbons. Even in countries which are politically committed to stringent climate change mitigation and energy security policies, new smokestacks are growing as fast into the sky as

* Corresponding author. Tel.: +31 224 565158.
E-mail addresses: michael.fuetterer@ec.europa.eu (M.A. Fütterer), lifu@mail.tsinghua.edu.cn (L. Fu), carl.sink@nuclear.energy.gov (C. Sink), s.degroot@nrg.eu (S. de Groot), manuel.pouchon@psi.ch (M. Pouchon), ywkim@kaeri.re.kr (Y. W. Kim), franck.carre@cea.fr (F. Carré), tachibana.yukio@jaea.go.jp (Y. Tachibana).

0149-1970/$ – see front matter © 2014 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.pnucene.2014.01.013

wind turbines. The onset of large-scale shale gas exploitation in the US has caused coal prices to drop significantly thus making electricity generation from coal the economically most attractive option for many utilities in many countries. Today, the global long-term trend towards increasing fossil fuel consumption appears almost unstoppable.

Obviously, coal combustion causes harmful emissions, not only the greenhouse gas CO_2, but also dust, heavy metals, NO_x etc. and is at the origin of large numbers of life cycle fatalities. As yet, Carbon Capture and Storage (CCS) is neither an economically established nor a publicly accepted technology and, for cost and efficiency reasons, it is likely not to be deployed where it would be needed the most. The alternative to CCS, Carbon Capture and Utilization, which is increasingly under discussion in several countries, requires large amounts of hydrogen to synthesize useful products (syngas, synfuel, plastics, construction materials etc.) from smokestack or atmospheric CO_2. Of course, this hydrogen has first to be produced by some form of low-carbon primary energy.

In addition, the sense of urgency to solve energy issues has weakened as a consequence of economic priorities dictated by the widespread financial crisis since 2008. Strategic long term decisions in the area of energy infrastructure are considered less acute now than economic and political short-term benefits.

Nonetheless, security of affordable primary energy supply is and will remain for the decades to come one of the most severe technical, economic and political issues and is possibly even key to a lasting economic upturn and a halt to de-industrialization of countries with stringent emission limits. Current energy policies direct most efforts towards “de-fossilization” of the growing electricity sector, although electricity generation represents typically only 30% of a country’s primary energy consumption. Therefore, changes in the other two big sectors (industry and transport) become increasingly pressing. Many countries consider it mandatory to domestically maintain strategically important industrial manufacturing capabilities of, for instance, fertilizers, chemical products, steel and, in several cases, a nuclear vendor industry along with the related jobs and tax income. Almost unnoticed by the public and political decision makers, these sectors consume very large amounts of fossil primary energy and are often enough incompatible with the low power density and variability of renewables.

While nuclear energy together with energy savings and development of renewables can be part of the answer to the described energy challenges, the Fukushima Daiichi accident has also emphasized the need for particularly safe reactor designs.

In this context, the attractive passive safety features of the medium-size (<600 MWth) Very High Temperature Gas-cooled Reactor VHTR stand out as a particular advantage. The VHTR was selected in 2002 among more than 100 proposals as one of six reactor concepts which had the potential to fulfill the performance criteria of the Generation IV International Forum (GIF). These include advances in sustainability (e.g. stretch fuel resources, minimize waste), economics (e.g. minimize CAPEX, OPEX, and LCOE), safety and reliability (e.g. robust safety architecture, no need for off-site measures) and proliferation-resistance & physical protection (e.g. absence of separated plutonium which could be illicitly diverged).

The VHTR is currently based on an open uranium fuel cycle, which at this time is not considered a sustainability issue given the long term availability of affordable uranium and the perspective to extract further uranium from seawater at defendable cost (Uranium 2011, 2012). While a VHTR is unsuitable for Pu breeding (indeed, it is better suited for Pu incineration), it could, once required, achieve long-term fuel sustainability based on the thorium-uranium fuel cycle. Reprocessing of VHTR fuel and integration of its fuel cycle into existing LWR or fast breeder reactor fuel cycles is no longer considered a challenge as suitable head-end processes could be demonstrated in the meantime. Another VHTR specific issue, the generation of graphite waste, is also being tackled by a European project proposing methods for decontamination and recycling of irradiated graphite.

Designed from the start to enable deployment in proximity of industrial sites and agglomerations, the VHTR capability to deliver heat above 600 °C to the end user makes them uniquely suited for cogeneration of process heat and electricity. This feature enables them for instance to efficiently produce hydrogen through steam electrolysis or thermochemical processes, to supply both hydrogen and high temperature heat for producing synthetic fuels from coal, biomass or captured CO_2, or to deliver high temperature heat and hydrogen or syngas as chemical reactants to a variety of industrial plants including petro-chemistry, fertilizer production and steelmaking. According to market studies performed in several countries, the potential market for this process heat is approximately as large as the electricity market and currently almost exclusively provided by fossil fuels with the concomitant CO_2 emissions.

The VHTR system can rely on operating experience acquired between the 1960s and now from experimental reactors and prototypes in the US (Peach Bottom, Fort St. Vrain), Germany (AVR, THTR), Japan (HTTR) and China (HTR-10), the latter two being operational.

Recognizing the potential benefit of the VHTR, the following countries gathered in the frame of the GIF and participate in R&D activities related to the VHTR: US, China, Japan, South Korea, France, Switzerland and the European Union. In addition, Canada contributes to the project on hydrogen production. South Africa, initially participating, has pulled out due to cancellation of their national development program while France will request observer status due to their national program focus on the sodium fast reactor system. The cooperation on VHTR under the GIF umbrella complements national projects and encompasses both, R&D in support of licensing near-term demonstrators (700–950 °C reactor outlet temperature) and the long term vision towards more demanding applications of this reactor type requiring even higher temperatures (950–1000 °C).

This paper first recalls the historical background of HTR technology and gives an overview of existing reactors and technologies. The motivations and priority applications of each participating country are explained. A section of this paper describes how VHTR system R&D is structured in GIF and quotes recent examples for the most salient results and future R&D priorities before addressing the current status of international demonstration projects.

Based on the past experience acquired since the 1960s on experimental high temperature reactors and prototypes, the attractive safety features of medium size HTRs, together with several development and demonstration projects worldwide confirm the VHTR as a system with a large market and CO_2 savings potential showing very active R&D cooperation with a high degree of achievement in the frame of the GIF.

2. Historical experience with demonstration and prototype reactor projects

Gas-cooled reactors were deployed originally for their simplicity and in quest for high power conversion efficiencies. The first commercial nuclear power plant was a CO_2-cooled Magnox reactor (Calder Hall, 1956). In total 26 Magnox reactors were built (270–1760 MWth) with one still in operation (Wylfa-1, 1971–2014) reaching the end of its service life in 2014. Later, 14 Advanced Gas-Cooled Reactors were built on 7 sites (~1200 MWe/site) in the UK with all AGR still in operation with high availability. From this initial experience, a considerable technical background for GCR could be gathered which was the basis for the development of High Temperature Gas-cooled Reactors: extremely clean primary cooling circuit, the use of a conventional steam cycle (~540 °C, same as for coal fired power plants) resulting in high thermal efficiencies (>40%), but still with a temperature limitation due to the use of CO_2.

The first High Temperature Reactor with a closed He primary loop was proposed in 1945 in the US but never built. It featured a primary circuit (helium at 1.55 MPa, 438–732 °C) coupled to a secondary Brayton power conversion cycle (air at 2.9 MPa, 677–22 °C) leading to an expected power rating of 5 MWe.

The pebble bed reactor was conceived in 1947 by the US American Farrington Daniels. This early vision was later developed to a power plant design by Rudolf Schulten in Germany.

In 1962–1963, a 3.3 MWth Mobile Low-Power Reactor (ML-1) with 140 (330 nominal) kWe was built in the US with a closed-cycle nitrogen turbine. The project was not pursued because it could not fulfill the power output expectations.

In 1964, the Experimental Gas-Cooled Reactor (EGCR) was built at ORNL in the US, but not completed. This was basically a helium-cooled AGR-type reactor using stainless steel fuel rod clusters. It should have produced 85 MWth/25 MWe with helium at 566 °C.

Ensuing developments led to conceptual changes in the existing gas-cooled reactors involving in particular the use of helium instead of CO_2 (avoidance of CO_2 dissociation and material carburization issues) and the substitution of metallic fuel clads by fully ceramic fuel, both in view of a further increase of reactor outlet temperature and improved safety performance.

The first tangible step in this direction was again made in the US by the construction of the Ultra-High-Temperature Reactor Experiment (UHTREX) which operated at LANL from 1966 to 1970. Its rated power was 3 MWth using helium at 3.4 MPa (870–1300 °C). It was the first reactor to use extruded fuel with TRISO coated particles in an annular rotatable core for on-line refueling.

The following developments led to basic technical characteristics shared by all modern HTR:

- can be built up to 600 MWth/core with passive safety features
- slow accident progression (large heat capacity, low power density)
- self-stabilization of transients (negative temperature coefficient)
- low source terms (fission product retention in fuel and structures)
- fully ceramic core (fuel and moderator/reflector)
- high-purity graphite as moderator/reflector, high thermal inertia
- chemically and neutronically inert helium as primary coolant
- high operating temperatures for high efficiency, capability for nuclear cogeneration of heat and power
- high burn-up capability
- high conversion ratios (high neutron economy and possible use of thorium)

One of the major challenges and the key to develop a fully ceramic reactor core was the development of the fuel. The initially used UO_2 or UC fuel was placed in ceramic clads which proved to show poor fission product retention. The coated particle fuel was invented in 1957–1961 by UKAEA and Battelle, but no patent was granted at that time. The UO_2 fuel kernels were made by precipitation of uranyl nitrate in ammonia and, after a heat treatment, coatings were deposited on top of these kernels via pyrolysis of hydrocarbons in a fluidized bed. The next development step was the early BISO particle fuel comprising a buffer layer directly deposited on the kernels and two PyC layers on top. Finally, modern TRISO particles were given an additional SiC diffusion barrier leading to confirmed fission product retention up to 1600 °C or even higher. These TRISO coated particles are the basis for all modern HTR designs. As shown in Fig. 1, they feature (from inside out) the kernel, a porous PyC buffer to accommodate fuel swelling and fission gases, a dense PyC buffer and a dense SiC layer as diffusion barriers against fission product escape, and a final PyC layer for better bonding with the matrix graphite into which they will be integrated. Typical dimensions are given in Table 1.

Baked into matrix graphite, the TRISO coated particles can now be given a macroscopic shape (cf. Fig. 2), usually in the form of thumb-thick cylinders (so-called "compacts") either solid or annular, or in the form of spherical fuel elements (so-called "pebbles", ∅60 mm). The compacts are inserted into hexagonal blocks made of graphite which are then assembled to constitute the reactor core contained in a pressure vessel.

Pebbles are filled into a reactor pressure vessel internally lined with graphite blocks and the resulting pebble bed constitutes the reactor core.

Based on these characteristics, in the 1960s two different types of reactors were designed and built, primarily to produce electricity. Experimental HTRs with a prismatic block core were developed in the UK (DRAGON reactor, operated 1964–1975, 21.5 MWth, an OECD project (Price, 2012)) and in the US (Peach Bottom, operated 1966–1974, 115 MWth/40 MWe (Beck et al., 2010)). They were followed by the prototype of the Fort St. Vrain Generating Station (operated 1976–1989, 842 MWth/330 MWe (Beck et al., 2010)). This reactor established the technical feasibility of HTRs even though it experienced problems of power fluctuations, jamming of a control rod and leakage of moisture into the core which finally caused its decommissioning for economic reasons.

Over the same period, Germany developed pebble bed reactors and built an experimental reactor (AVR, 46 MWth/15 MWe (Pohl, 2008)) at the Jülich Research Centre that successfully operated from 1967 to 1988 and produced valuable feedback on pebble fuel and overall reactor operation. In particular it was used for several demonstrations of passive safety performance and survived a water ingress accident provoked by a steam generator leak. Following this experience, a 300 MWe prototype power reactor that was aimed at using thorium fuel was built and operated: the Thorium High Temperature Reactor (THTR-300, 750 MWth/300 MWe, Baumer and Kalinowski, 1991). This prototype, however, met a number of

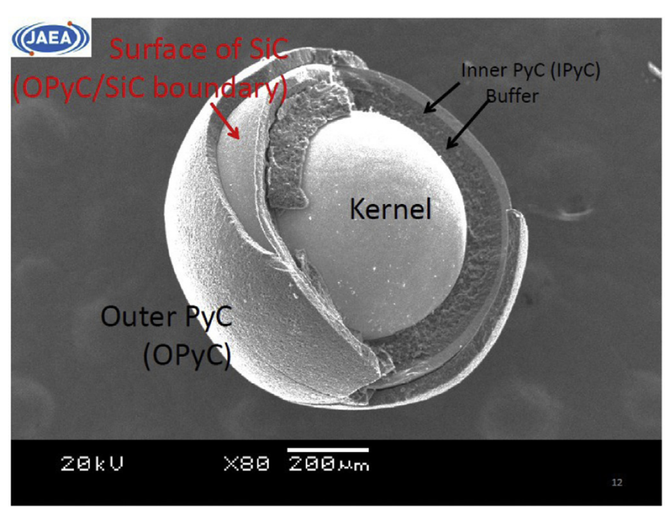

Fig. 1. Cut-away SEM picture of a modern TRISO coated particle with indication of the coatings.

Table 1
Typical examples for nominal characteristic data of German AVR GLE-4 particles and pebbles and US NGNP particles and compacts.

Coated particle	AVR pebble	NGNP compact
Kernel composition	UO_2	UCO
Kernel diameter [μm]	502	425
Enrichment [U-235 wt.%]	16.76	14
Thickness of coatings [μm]		
Buffer	92	100
Inner PyC	40	40
SiC	35	35
Outer PyC	40	40
Particle diameter [μm]	916	855
Fuel element (pebble or compact)		
Dimensions	∅60 mm (spherical)	∅12.3 × 25 mm (cylindrical)
Heavy metal loading [g/FE]	6.0	1.27
U-235 content [g/FE]	1.00	0.18
Number of coated particles per FE	9560	3175
Volume packing fraction [%]	6.2	35
Defective SiC coatings	7.8×10^{-6}	$<1.2 \times 10^{-5}$
Matrix type	A3-3	A3-3
Matrix density [kg/m^3]	1750	1600
Temperature at final heat treatment [°C]	1900	1850

technical difficulties. In retrospective its design seems to have been extrapolated in power too quickly. Examples of design issues are the direct insertion of the control rods in the pebble bed (pebble damage) and the pebble withdrawal system. The THTR was closed in 1989 in the aftermath of the Chernobyl accident after only three years of operation.

In the same period, the Power Nuclear Project (PNP-500, 500 MWth (Neef and Weisbrodt, 1979)) in Germany aimed at using nuclear heat to produce hydrogen through steam methane reforming. This project led to development and testing of large modules of heat exchangers and a steam reformer. It was brought to a halt in 1989 thus marking a temporary stop of HTR development in the world.

In the 1980s, Interatom/Siemens in Germany developed the 200 MWth HTR-Modul as the first modular pebble bed design consisting of a metallic reactor pressure vessel connected to an adjacent steam generator through a hot gas duct (Hochtemperaturreaktor-Mo, 1988). The concept features a simplified design with a size and power rating chosen to enable passive decay-heat removal after a loss-of-coolant-accident solely by conduction and radiation. No convection is necessary (Reutler and Lohnert, 1984). The HTR-Modul is the basis for the HTR-10 and HTR-PM reactors in China.

The Gas Turbine Modular Helium Reactor (GT-MHR (LaBar, 2002)) is a 600 MWth design developed by a group of Russian and US enterprises, Framatome in France and Fuji Electric in Japan. It employs an annular prismatic core and utilizes a direct helium Brayton cycle for electricity generation with an efficiency of up to 48% based on a reactor outlet temperature of 850 °C. Extensive analysis has shown that this reactor, and more generally most HTR designs, are particularly suitable for the incineration of excess plutonium which became an issue in the US and in the former USSR for the implementation of the START I disarmament treaty in 1991. Hydrogen production with the S–I process was also envisaged. The Preliminary Design of the reactor plant and GT-MHR prototype power plant was completed in 2001. The GT-MHR regulatory process started in 2002 but was not completed. More recently, the GT-MHR design was proposed by General Atomics as one of the options for the US NGNP project until the NGNP Alliance expressed in 2012 a preference for the ANTARES concept developed by AREVA (Lommers et al., 2012), based on the GT-MHR but with an indirect steam cycle. The GT-MHR was also the basis for the Japanese GT-HTR300 designed by JAEA (Kunitomi et al., 2004).

A summary on the 7 built reactors (Dragon, Peach Bottom, Fort St. Vrain, AVR, THTR, HTTR and HTR-10) can be found in Beck et al. (2010). The experience of past experimental and prototype HTRs demonstrated their technical viability, however, they were not given the time to prove their economic competitiveness with LWR for electricity production. No further developments were to occur until the late 1990s when the interest in HTRs was revived by needs of low carbon high temperature heat supply for a variety of industrial processes.

One of these new projects was the Pebble Bed Modular Reactor (PBMR (Matzner and Letcher, 2008)) in the Republic of South Africa. PBMR Pty. Ltd. is a public–private partnership that was established in 1999 in response to threats of nation-wide power outages and to initiate the development of a modular pebble-bed reactor with a rated capacity of 165 MWe. This design featured a thermal power of 400 MWth and a direct power conversion with a gas turbine operating with a helium outlet temperature of 900 °C. In June 2003 the South African government approved a prototype of 110 MWe for the utility Eskom on the site of Koeberg. This prototype that was

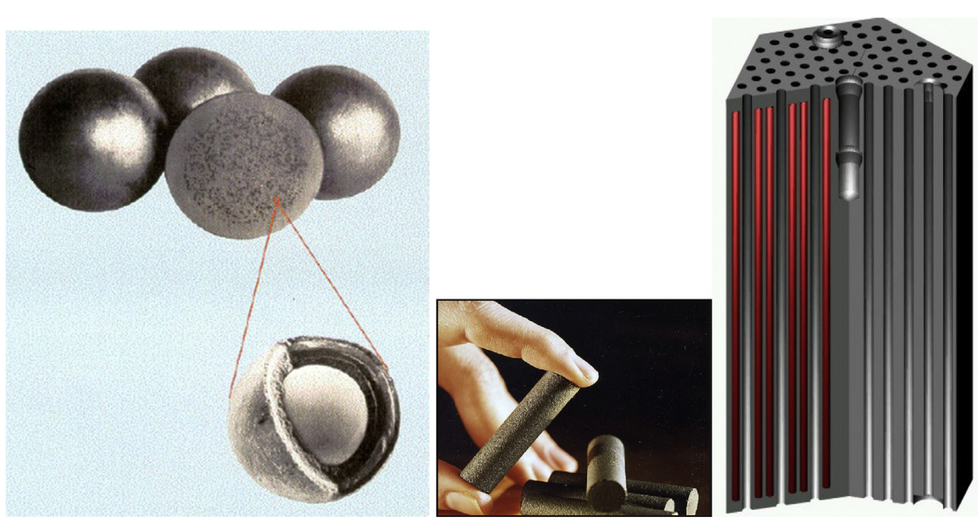

Fig. 2. Macroscopic forms of VHTR fuel: pebbles (left), compacts (middle) and compacts placed in a hexagonal graphite block (right).

intended to be put in service in 2014 was meant to precede a fleet of 24 PBMRs so as to make up 4000 MWe out of the 12,000 MWe additional nuclear capacity planned by 2030. Large facilities dedicated to PBMR specific technologies testing have been realized in 2007: a “Heat Transfer Test Facility”, a “Helium Test Facility”, a “Pebble Bed Micro Model” and an “Electro-magnetic blower”. A fuel laboratory developed manufacturing processes and quality assurance testing techniques in collaboration with NECSA and successfully manufactured coated fuel particles with enriched uranium in December 2008.

In 2009 the PBMR project, like other projects of nuclear equipment in South Africa, faced funding difficulties and had its business plan re-oriented towards the supply of industrial process heat, a difficult task in a country with large coal reserves and no CO_2 emission limits. The new focus of the PBMR was on onsite power, cogeneration, seawater desalination and direct process heat delivery. Target process heat applications included coal-to-liquid or gaseous fuels, petrochemicals, ammonia/fertilizer, refineries, steam for oil sand recovery, bulk hydrogen for future transportation and water desalination. Thus, PBMR Ltd. started developing options for commercial fleets with Sasol (the South African coal liquefaction company), with the utility Eskom for electricity, as well as with US and Canadian cogeneration end users including oil sand producers. The PBMR project was accordingly revisited to develop one standard design that meets all requirements for these applications, thus leading to a cogeneration steam plant with a power of 200 MWth, a helium temperature of 750 °C at core outlet and a steam generator directly placed in the primary loop. A conventional subcritical steam turbine was selected for first generation plants whereas super-critical cycles were envisaged for next generation plants.

Due to funding issues and problems in the interaction between PBMR and the South African regulator the project was put on ice in 2010. A critical analysis of this development is given in Thomas (2011).

3. Overview of currently operating VHTRs

First, the Japan Atomic Energy Agency (JAEA) built a research reactor in Oarai, the High Temperature engineering Test Reactor (HTTR (Kunitomi, 2013), Fig. 3). It is a prismatic block type reactor with annular compacts. It was put in service in 1998 and reached its full design power of 30 MWth in 2001 with a helium outlet temperature of 850 °C. Subsequent tests until 2010 have demonstrated the safe behavior of the reactor. This included reactivity insertion as well as partial and complete loss of forced cooling, but not yet at full

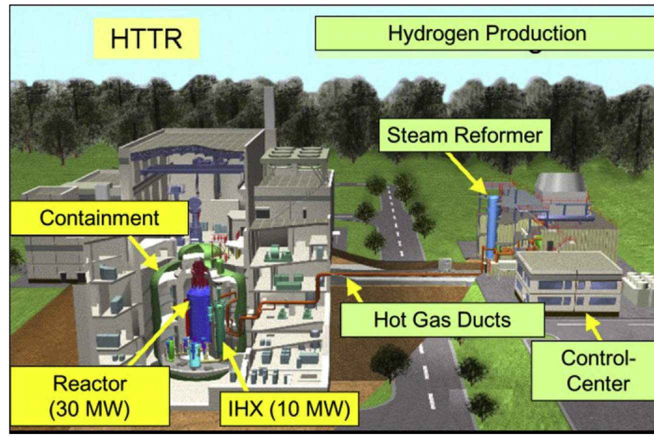

Fig. 4. Schematic of HTTR and future heat use facilities.

power. The HTTR was successfully operated at the design temperature of 950 °C first in 2004, then for 50 continuous days in 2010. In parallel with tests on the HTTR, JAEA is developing the sulfur-iodine thermo-chemical process to produce hydrogen (Fig. 4). A first demonstration of this process was achieved in 2003 when a continuous production of 30 l/h of hydrogen was maintained for several days. After the March 2011 earthquake which triggered the Fukushima accident, the HTTR was only slightly damaged. After extensive inspection and some repair, a restart is scheduled for early 2015 after review by the regulator. It is planned to conduct further safety tests in the frame of an OECD–NEA Loss of Forced Cooling Project which started in 2011.

The Institute of Nuclear and New Energy Technology (INET) of the Tsinghua University in China has built the experimental reactor HTR-10 (10 MWth (Yujie, 2012), Fig. 5) that was put into service in 2000. The successful operation of this reactor demonstrated an updated pebble bed core HTR technology. In particular it served as a test bed for fuel, components and for code validation. With several successful demonstrations of its benign safety performance for the public and the licensing authority it paved the way for scaling up this technology to the High Temperature Reactor – Pebble bed Module (HTR-PM, 210 MWe) project. The HTR-10 was also used for district heating of the INET campus in the vicinity of the reactor.

Together with their ancestors, HTTR and HTR-10 have already significantly contributed to establish a rather high technology readiness level both for block type and pebble bed reactor cores.

Fig. 3. External view of the HTTR building in Japan.

Fig. 5. External view of HTR-10 building in China.

4. Applications for VHTR systems

Already with earlier reactor types, nuclear cogeneration was performed in many countries and with several types of reactors including LWR, HWR and SFBR. District heating (80–150 °C) is probably the most widely found application of nuclear heat: 46 reactors in 12 countries, including for instance Slovakia, Switzerland, Russia and China were and are used for this purpose.

Examples for existing low temperature applications of nuclear heat include seawater desalination (Japan, Kazakhstan), paper and cardboard industry (Norway, Switzerland), heavy water distillation (Canada) or salt refining (Germany).

The technology options for nuclear process heat utilization with High Temperature Gas-cooled Reactors were already documented quite early (Schulten, 1976). A survey of two decades of activities in Germany is given in Verfondern (2007a) and further potential is outlined in Verfondern (2007b).

The VHTR produces heat at a much higher temperature level (exergy) than LWR. This opens the possibility to replace a large number of existing industrial cogeneration plants delivering process steam in the 500–600 °C temperature range. Very significant amounts of such process steam are consumed in the chemical and petrochemical sector as well as in the fertilizer industry, where today this steam is mostly produced by gas or coal firing.

For several of the GIF member states, in particular those where natural gas is expensive, the prospect of hydrogen production is still the main driver to work on the VHTR system. As a matter of fact, process heat from a VHTR can be used for several more or less advanced methods of hydrogen production. The most near term option is steam methane reforming of natural gas with steam at 700 °C, 5.5 MPa. Owing to the external heat supply, more than a third of natural gas is saved. In the 1980s, the necessary components, e.g. heat exchangers or reformers, were developed and tested under nuclear conditions in Germany and in Japan (Harth et al., 1990).

Processes and components for allothermal and steam coal gasification processes were also tested in Germany. They require typically steam in the range of 750–900 °C at 0.1–4 MPa. Although external heat supply makes coal upgrading more efficient, these processes release large amounts of unwanted CO_2.

These activities were brought to a temporary halt in an antinuclear climate after the Chernobyl accident, with inexpensive oil and gas and in absence of CO_2 emission restrictions.

As steam methane reforming consumes natural gas and generates CO_2 emissions in the process, direct water splitting methods are under investigation in the GIF VHTR system as a clean alternative. Today, the most prominent are High Temperature Steam Electrolysis (750–950 °C) where a part of the required water dissociation energy is delivered in the form of heat, and thermo-chemical cycles such as the Iodine–Sulfur Cycle where one of the three process steps (SO_3 decomposition) requires heat input at 850 °C.

The market for bulk hydrogen is currently very large and growing fast, with distribution networks in place already in several countries. To justify large scale production of hydrogen, the development of a specific "hydrogen economy" is not required. Hydrogen uses include upgrading of increasingly heavy oils to lighter fractions, hydrogenation processes, hydro coal gasification, metal refining, ammonia production for fertilizers, the synthesis of methanol or synfuel, or the use of hydrogen in combination with fuel cells as a transport fuel. For some Asian countries, the replacement of coke by hydrogen for direct iron ore reduction is of particular interest to cut back emissions from steel making. Finally, hydrogen can also play a role in carbon capture and utilization processes which would use CO_2 together with hydrogen as a feedstock for the fabrication of a wide array of possible products ranging from plastics or synfuel for aviation to construction materials. A summary of such processes and products is provided in Styring et al. (2011).

In the context of energy system integration efforts with growing fractions of variable renewable electricity in many countries, it is of particular interest that the cogeneration capability of VHTR would allow it to contribute to grid stabilization ("peak shaving"), e.g. by modulating the production of (storable) hydrogen depending on the electricity demand in the grid, similar to what is currently envisaged for wind energy ("power to gas").

To further corroborate the incentive for process heat and hydrogen production with nuclear energy, several market research, economic analyses, trade studies, and business plans were recently prepared in several GIF countries, some of which are publicly available (e.g. Angulo et al., 2012; Bredimas, 2012; Energy Development Opportunities for Wyoming, 2012; Konefal and Rackiewicz, 2008; Shropshire, 2013).

5. Structure of GIF VHTR R&D and benefit from collaboration within GIF

The potential of a VHTR at 900–1000 °C to match temperature requirements for advanced hydrogen production processes based on electro- or thermo-chemical water splitting processes was the initial driver for this reactor type. Missions of the VHTR have expanded since then to cogeneration of electricity and process heat for various industrial applications. The VHTR system experienced sustained interest from all active members of the GIF since its beginning. The VHTR System Arrangement was signed in November 2006 by Canada, Euratom, France, Japan, the Republic of Korea, Switzerland and the United States. The People's Republic of China signed this Arrangement in October 2008. The OECD/NEA provides the Technical Secretariat and data management resources to the GIF structure.

Multinational cooperation in the GIF complements national R&D efforts for current projects in the reactor outlet temperature range of 700–950 °C and also develops technology breakthroughs for the VHTR aiming at even higher temperatures. The current consensus is that 950 °C is the temperature limit for classical structural materials. Higher temperatures would call for a significantly larger development effort with a long-term timeline.

In the GIF VHTR system, four common projects were set up. Those on "Fuel and Fuel Cycle" and "Hydrogen Production" became effective in January and March 2008 and a third project on "Materials" became effective in April 2010. A fourth project on "Computational Methods, Validation and Benchmarking" was ready for signature in 2010 but was then put on hold due to the withdrawal of South Africa which held an important position in this project. Discussions are currently underway about how to adequately reformulate this project and to redistribute the intended work plan among interested project partners which would cover especially the development of tools required for licensing. A fifth project on "System Integration and Assessment" looking at the entire reactor, at the end-user systems for process heat and, importantly, at their interface, has been under discussion regularly and could help in providing guidance for the other projects.

Since 2009, Canada has limited its contribution to the hydrogen production project and France has announced to request, after completion of its commitments, observer status due to the French priority on the sodium-cooled fast reactor.

Cooperative work on TRISO fuel includes sharing irradiation experiments, post-irradiation evaluation facilities and constituent materials properties. Cooperation on hydrogen production processes enabled the realization of common laboratory scale experiments on the thermochemical S–I process and on HTSE, to advance the development of catalysts and share results of technical and economic assessments of various processes. Cooperative development of materials covers graphite, nickel-base alloys and 9% Cr ferritic-martensitic steels, and composite ceramics. Results are compiled in a common data base with restricted access which is operated by ORNL.

Specific Agreements were worked out to frame exchanges between cooperative R&D in the GIF and VHTR related projects so as to assure a fair treatment of R&D results generated by GIF members and their privileged access to operating parameters of future prototype reactors in equitable conditions.

Although not specifically oriented towards a hexagonal block or pebble bed design, all projects are geared to raise the technology readiness to the level required for generating a basic plant design which is a prerequisite for a licensing application. In all cases, this cooperation is yielding significant advantages for the involved project partners. Initially, a wealth of historical experience was collected and shared in the form of documents, dedicated workshops or fuel and material samples. This exchange included properties data, fabrication, irradiation and post-irradiation testing methods, quality assurance, design and analysis tools and methods, as well as the experience in building and operating related equipment. In the course of the project execution, time, effort and scarce facilities (such as irradiation space or hot cell equipment) are shared, and in doing so they accelerate progress and create synergies. The sections which follow highlight some of the most recent achievements in these projects, some of which are also mentioned in the GIF Technology Roadmap Update (2013).

5.1. Materials

This project bundles the efforts to develop, screen and qualify the materials required for a VHTR and its ancillary equipment including components such as pipework, gas circulators, heat exchangers, valves, graphite moderators or control rods. This encompasses graphite, advanced nickel-base alloys and ferritic-martensitic steels of the 9% Cr class, as well as composite ceramics. Test campaigns are defined in common and the work is shared. Mechanical and corrosion tests are conducted to screen candidate materials and to acquire the data needed for extending current design codification rules to VHTR service conditions, and for licensing prototypes. Results are compiled in a common data base operated by the Oak Ridge National Laboratory. The 9Cr1Mo alloy was identified as a promising candidate for a hot reactor pressure vessel operating at 400–450 °C (i.e. beyond the limits of the low alloy Mn–Mo–Ni SA-508 steel commonly used in PWRs). Two conventional nickel-base alloys (617 and 230) were also characterized at temperatures ranging from 700 °C to 1000 °C in terms of mechanical properties and corrosion resistance (impurities in helium coolant) for use as structural material, in particular in thermo-mechanically loaded components such as heat exchangers. Design efforts in the US for VHTRs at higher outlet temperatures have indicated that engineering solutions will allow the use of traditional LWR pressure vessel steels (SA-508/SA-333) for the VHTR. US efforts have focused on developing the data needed to allow use of LWR pressure vessel steels in a VHTR environment. This data is being incorporated into the ASME Code for use in gas-cooled reactors. Metallic core structures and cooling systems, such as intermediate heat exchanger, hot gas duct, process components, and isolation valves that are in contact with the hot helium can use the current metallic materials up a core outlet temperature of about 700–800 °C. Efforts have focused on developing the data needed to extend Alloy 800H for use up to 850 °C and Alloy 617 for use up to 950 °C. Within the next four years all of the data needed to codify these materials will be provided to ASME.

The incentive and reward to share work is particularly high in the area of irradiation testing which is performed in the US, Switzerland and in the EU. As an example, various grades of graphite were and are being irradiated at different temperatures and neutron fluences to determine their shrinkage-swelling curves. These curves will be used in new design standards and determine the expected service life of in-core graphite components before they have to be replaced. Significant progress was also made in the area of manufacturing, testing and qualification of compact heat exchangers including tests of mockups in helium loops. A sketch of a printed circuit intermediate heat exchanger is shown in Fig. 6.

Areas of further common R&D were identified and include the development, testing and qualification of new high temperature alloys, new graphite types and ceramic composite materials. To maximize synergies, the VHTR materials project further envisages closer crosscut cooperation with other GIF projects on subjects of common interest, for instance the development of harmonized test methods, new codes and standards for known and new materials in relevant operating conditions including combined effects of corrosion, creep, fatigue and irradiation.

Carbon–carbon and/or SiC/SiC composites may be needed for control rod sheaths, especially at the higher outlet temperatures for the VHTR anticipated in a prismatic block core, so that the control rods can be inserted into the high-temperature areas of the core. Promising ceramics such as fiber-reinforced ceramics, sintered alpha silicon carbide, oxide-composite ceramics, and other composite materials are also being developed for other industrial applications needing high-strength, high-temperature materials. Work continues around the world on C/C and SiC/SiC composites for a variety of nuclear applications. Irradiation stability of some SiC/SiC composites has been demonstrated up to 70 dpa. Novel fabrication routes, development of hermetic composites, irradiation testing and establishment of design rules to enable use in a nuclear system are the focus of R&D over the next 10 years.

Core internal structures containing the fuel elements such as pebbles or blocks are made of high-quality graphite. The performance of this graphite has been demonstrated in gas-cooled pilot and demonstration plants, but recent improvements in the manufacturing process of industrial graphite have shown enhanced oxidation resistance and strength. Irradiation tests are needed to qualify components using advanced graphite or composites to the fast neutron fluence limits of the VHTR. Current irradiation testing in the United States and Europe is qualifying a number of current generation grades of nuclear graphite from the major graphite vendors. Irradiation and post-irradiation examination are

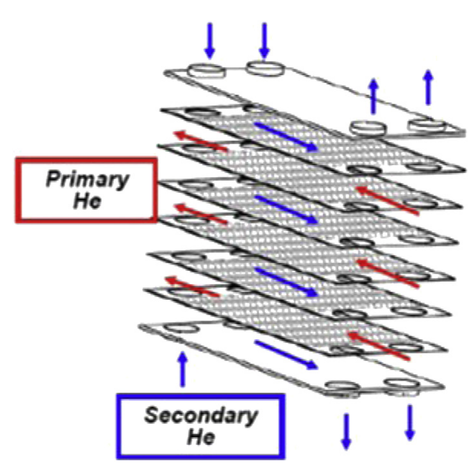

Fig. 6. Sketch of a printed circuit intermediate heat exchanger.

underway. Fig. 7 graphically shows the objectives in terms of temperature and neutron fluence of past and current graphite irradiation tests. Preliminary data suggest the performance is acceptable. Full qualification of current grades of graphite is expected in the next decade. Work is also planned to harden graphite against structural degradation from air or water ingress.

5.2. Fuel and fuel cycle

In this project, cooperative work on TRISO fuel includes sharing irradiation experiments, characterization methods and facilities as well as the determination of materials properties. Advanced fuel particles such as UCO fuel and ZrC (instead of SiC) coated particles are also investigated. GIF contributed to sharing the effort to re-establish the fabrication and qualification capability of standard TRISO coated fuel particles in several countries.

Significant effort was shared also in the area of fuel qualification for licensing purposes. This includes several steps:

- Pre-irradiation characterization: This is as a quality assurance method to check the size, integrity and roundness of coated particles, the particle distribution in a compact or pebble, and the resistance of these fuel elements against external influences such as shocks or vibration. These techniques are especially useful to upscale laboratory fabrication methods to an industrial scale.
- Irradiation testing: In material test reactors the fuel elements are exposed to high temperatures and have to endure a significant burn-up and fast neutron irradiation damage up to or even beyond their design limit (Fig. 8). During the irradiation, possible release of fission gases is monitored and must remain very low. Every such irradiation test typically has a duration of several years, not counting the time for preparation and post-irradiation work.
- Safety testing: The irradiated fuel elements are placed in a furnace and heated to temperatures beyond the maximum that the hottest part of a reactor core will reach during a depressurized conduction cool down accident. If at these temperatures the release of fission products from the fuel remains very low, the fuel can be considered as qualified.
- Post-irradiation examinations: To understand the reasons for good performance, to appreciate the performance reserves of irradiated fuel and to understand fission product migration mechanisms, the fuel undergoes a palette of highly specialized analytical techniques from macroscopic to nanometer scale.
- Code development: Results from the various test stages are translated into models that enable the prediction of fuel performance in specific codes;

Similar to the Materials project, the cooperation on fuel benefits significantly from sharing irradiation tests. A particular highlight

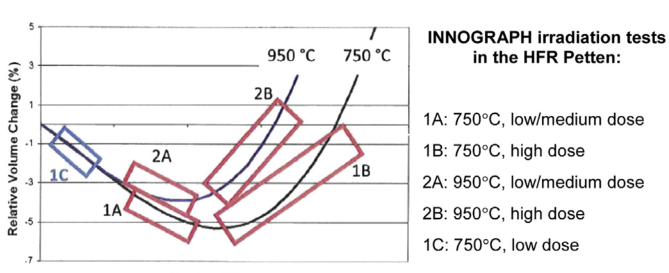

Fig. 7. INNOGRAPH-1C graphite irradiation test with focus on early part of the shrink–swell curve.

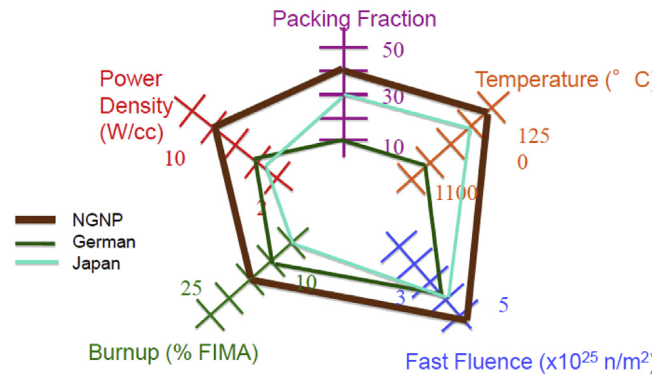

Fig. 8. Performance envelope for NGNP TRISO fuel is more aggressive than previous German and Japanese qualification efforts.

was the offer from the US to have fuel samples from other project partners irradiated together with recently fabricated US fuel in the irradiation test AGR-2 in the Advanced Test Reactor (ATR) at INL. The irradiation comprised US, French and South African fuel. It began in 2010 and reached its target fluence in the end of 2013 with no fuel failure observed. Significant efforts also went into the exchange of methods and techniques used in the various stages of fuel qualification, for instance the organization of specific workshops on post-irradiation examinations and on safety testing.

In the US and China, fabrication activities are demonstrating that UO_2 and UCO TRISO fuel can be fabricated to the high quality/low defect levels necessary for the concept. Irradiation testing of spheres manufactured in China has demonstrated performance as good and in some cases better than the historical German experience. US efforts indicated that UCO TRISO fuel is capable of burnups approaching 200 GWd/t_{HM} at temperatures of ~1250 °C.

This GIF project has organized in July 2013 a workshop specifically dedicated to safety testing of fuel where information on design of test equipment, test methods, technical difficulties and their solutions as well as test results were exchanged. Fig. 9 shows the main chamber of the new Fuel Accident Condition Simulator device which was installed and first used at INL in spring 2013.

Accident safety testing of US UCO TRISO at and beyond projected accident conditions has demonstrated a high degree of robustness for hundreds of hours at 1600, 1700 and 1800 °C. A US fuel vendor has been established that is capable of producing either UO_2 or UCO TRISO fuel in compact form. Work is planned to continue in both China and the US to complete qualification of these fuels within the next decade. In the long term, an increase of the core-outlet temperatures to around 1000 °C for the entire plant lifetime can be envisaged raising maximum fuel temperatures under accident conditions up to 1800 °C and maximum fuel burnup of 150–200 GWd/t_{HM}.

Above a fuel operating temperature of 1200 °C, new coating materials such as ZrC and/or improved coating techniques have been considered. Use of ZrC in VHTRs enables an increase in power density and an increase in core power with the same coolant outlet temperature. It displays greater resistance to chemical attack by the fission product palladium. Under accident conditions, historical data suggest that the ZrC-TRISO fuel may be more robust than traditional SiC TRISO fuel. However, unexplained anomalous historical results, the susceptibility of ZrC to oxidation, and recent data suggesting significant thermomechanical material property degradation under accident conditions have reduced the interest in pursuing the ZrC option. Both the historical and more recent fabrication data on ZrC indicates it is more difficult to fabricate than SiC. Furthermore, the outstanding behavior of SiC coated TRISO fuel

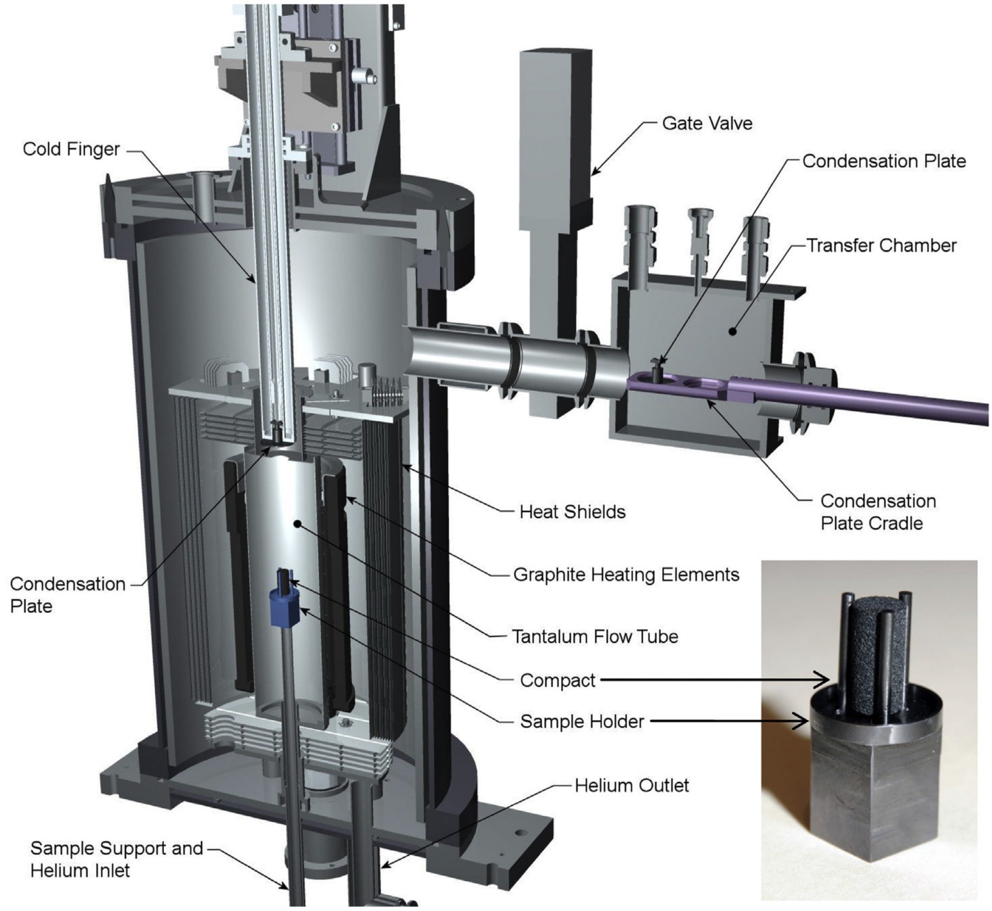

Fig. 9. Main chamber of the Fuel Accident Condition Simulator at INL and sample holder for irradiated fuel compact.

may be sufficient to meet the high temperature irradiation needs for the VHTR.

The management of spent fuel and of used graphite is also included in this project.

The VHTR baseline for GIF assumes a once-through LEU (<20% ^{235}U) fuel cycle. Like LWR spent fuel, VHTR spent fuel could be disposed of in a geologic repository or conditioned for optimum waste disposal. The current VHTR particle fuel coatings form an encapsulation for fission products that is extremely resistant to leaching in a final repository. However, as removed from the reactor, the fuel includes large quantities of graphite, and research is required to define the optimum packaging form of spent VHTR fuels for long-term disposal. Radiation damage will require replacement of some graphite components every 4–10 years.

Fuel recycling of LWR and VHTR spent fuel in a symbiotic fuel cycle can achieve significant reductions in waste quantities and radiotoxicity because of the VHTR's ability to accommodate a wide variety of mixtures of fissile and fertile materials without significant modification of the core design. This flexibility was demonstrated in the AVR test reactor in Germany and is a result of the ability of gas-cooled reactors to decouple the optimization of the core cooling geometry from the neutronics.

For an actinide burning alternative, specific Pu-based driver fuel and transmutation fuel containing minor actinides would have to be developed. This fuel may benefit from the R&D on SiC and ZrC coatings mentioned above but will need more R&D than LEU fuel.

Analytical and experimental efforts over the past decade in the EU and US have evaluated both direct disposal and fuel recycling for VHTR materials. Routes to deconsolidate fuel pebbles or compacts have been established and head end processes developed to work with either aqueous or pyro-processing recycling routes.

The related results of the EU CARBOWASTE project were made available to GIF. It was confirmed that in principle fuel waste volume reduction, recycling and reprocessing are possible also with TRISO fuel particles. A commercially available head-end process using electro-hydraulic shock waves created by pulsed currents under water was successfully demonstrated on dummy coated particles and on pebbles to separate matrix material from coated particles. With the same method but different operating parameters the coated particles could be cracked so that further fuel waste reduction and/or recycling can be envisaged now. Another consequence is that synergies with fuel cycles of other reactor types, or advanced fuel cycles can be envisaged.

To solve another issue of graphite moderated reactors which is the large amount of irradiated graphite waste at decommissioning, the same fragmentation methods were also successfully tested on graphite as a head-end process for decontamination, ^{14}C removal and ultimately recycling of irradiated graphite. Preliminary efforts on graphite recycling suggest that the material can be an acceptable feedstock for re-fabricated graphite.

5.3. Hydrogen production

While process steam generation was rather recently identified as a large market opportunity for VHTR in the nearer term, the longer term objective and initial driver towards reactor outlet temperatures of the VHTR in the vicinity of 1000 °C was the thermo-chemical iodine-sulfur process for efficient large-scale hydrogen production which involves a process step at 850 °C. Even without the advent of a possible future "hydrogen economy", the market for hydrogen is already today very significant and growing at a fast pace, for instance in petrochemistry and fertilizer factories. Producing this hydrogen without the currently employed steam methane reforming process would save large amounts of natural gas and the concomitant CO_2 emissions. The benefits are even larger when hydrogen replaces coke for iron ore reduction in steel making. A recent summary of nuclear hydrogen production processes can be found in Yan and Hino (2011).

Cooperation within GIF contributed to share the realization and results of laboratory scale experiments on the S–I and HTSE processes, to advance the development of catalysts and to share results of technical and economic assessments of several processes. An example of shared experimental work consisted in an Integrated Laboratory Scale experiment of the S–I thermochemical process that was jointly built and operated by CEA, SNL and General Atomics in 2007–2008 on the site of the latter in San Diego. This experiment was designed for a production rate of 100 l/h. It confirmed the difficulty to manage iodine in chemical processes, and contributed, together with economic analyses, to a decision that France, the US and Canada would prioritize their research on HTSE as the most attractive alternative. HTSE has completed testing at high pressure, a key item for integration into an energy conversion system. Second generation solid oxide fuel cells are demonstrating much lower degradation than first generation cells. Fig. 10 shows a solid oxide electrolysis cell stack assembly and test. The technology has matured enough to support near-term commercial scaling and deployment by industry.

Current cooperation within this project includes:

- Shared laboratory-scale experiments to establish the feasibility and performance of hydrogen production processes
- Reduction of temperature requirements through the use of catalysts and maximization of efficiency through integrated process optimization
- Cost reduction of components and increase of useful service life
- R&D to establish optimized flow sheets and to assess technical/economic aspects
- Development and assessment of coupling technologies as the interface between the reactor and the hydrogen production process
- Establishing common plans for upscaled next step tests in the range of 0.5–1 MW as well as for pre-industrial integrated process demonstrations with the HTTR and future HTR projects
- Upscaling to commercial scale

On the way towards these objectives, the Asian project partners are currently building components, chemical reactors and processes as well as laboratory scale equipment in the range of 50–200 l/h H_2 using S–I. On the other hand, the EU, France, Canada and the US develop and optimize HTSE.

Beyond experimental testing, significant analytical capabilities/methods were developed that can be used to evaluate hydrogen production in combination with a VHTR plant.

6. Status of new national projects

The interest for cooperation on the VHTR system within GIF is driven by a number of national R&D and demonstration programs in the signatory countries. This section shortly describes their motivations and current program status.

6.1. China

In 2005, China announced its intention to scale up the HTR-10 technology (Wu et al., 2002) and to realize a national project of a commercial plant based on independent intellectual property rights (Zhang et al., 2006). Inspired by the HTR-Modul design by Interatom, the HTR-PM demonstration plant consists of two reactor modules of 250 MWth each with a helium core outlet temperature of 750 °C that drive together a common steam turbo-generator set rated at 210 MWe with steam conditions typical for Chinese coal fired power plants (566 °C) and yielding a power conversion efficiency of approx. 40%. These relatively conservative operating conditions and the production of electricity instead of cogeneration of heat and power were deliberately chosen to minimize risk at this stage (Zhang et al., 2009). Construction activities had begun in 2009. After a temporary halt for nationwide safety reviews after the Fukushima accident, first concrete for HTR-PM was poured in December 2012. The plant is situated in Shidaowan in the Province of Shandong with plant operation expected to start around the end of 2017. China has the intention to develop a larger fleet later on.

Further design activities, component manufacturing and construction are pursued in parallel to full scale tests of key components which will be shared with GIF. The construction of a fuel pebble manufacturing facility started in March 2013 aiming at first production in 2015. A fuel pebble irradiation for qualification purposes is underway in the HFR Petten in the Netherlands. Other activities relevant for GIF include the set-up of a hydrogen production test facility with a target of 200 l/h in 2014, as well as code verification and validation.

Future developments benefit from the fact that HTR-PM is designed to ultimately achieve a core outlet temperature of 950 °C with current core design and fuel element technologies. The modular nature of the HTR-PM also accepts more ambitious power conversion systems and process heat delivery.

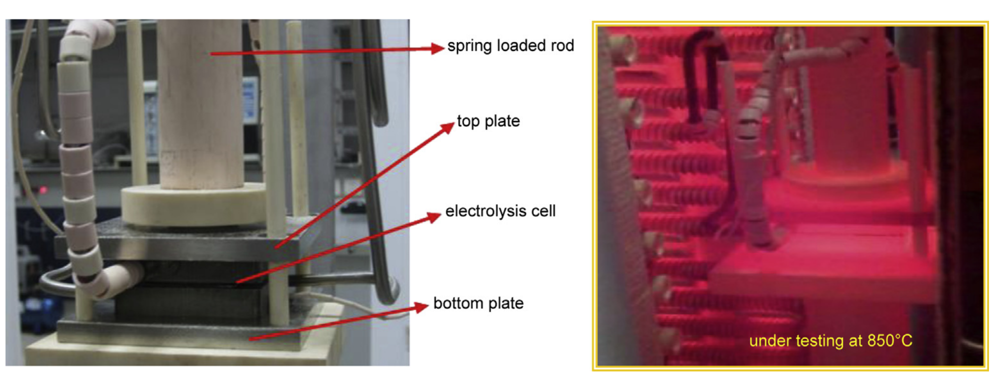

Fig. 10. Solid oxide electrolysis cell stack assembly and test.

6.2. USA

In the US, the Next Generation Nuclear Plant (NGNP) project was mandated by the US Energy Policy Act of August 8, 2005 as a high-temperature gas-cooled reactor intended for high-efficiency electricity production, high-temperature process heat generation, and nuclear assisted hydrogen production at INL. It would be co-located with an industrial plant that would use process heat from the reactor and could operate in 2021. Pre-conceptual and conceptual design studies had concluded that there were no discriminating technical factors that would favor pebble bed or prismatic design over another and that the initial gas outlet temperature would be in the 750–800 °C range to meet most end-user needs.

Pre-conceptual design studies have been conducted under contracts awarded in 2006 and 2008 by the US-DOE to the three vendors AREVA, General Atomics and Westinghouse. General Atomics and AREVA were putting forward their GT-MHR and ANTARES concepts of prismatic block-type reactor whereas Westinghouse with the support of PBMR was supporting a Pebble Bed Modular Reactor.

The NGNP project took another step in August 2008 when the US-DOE and the NRC submitted a joint licensing strategy which would lead to a framework for vendor submission of a license application. DOE has examined partnering strategies with industry (nuclear vendors and potential users of process heat in sectors such as oil, chemistry or steelmaking gathered in the "NGNP Industry Alliance") to drive the development of the NGNP project.

Since then, the NGNP Industry Alliance has expressed in 2012 a preference for the prismatic block type ANTARES proposed by AREVA which employs an indirect power conversion system. It has also conducted various feasibility, economic and market studies on the use of process heat in a number of different states and for different purposes. A large process heat market was identified which could be satisfied with reactor outlet temperatures in the 750–800 °C range. The NGNP Alliance work hints at an economic feasibility of nuclear process steam generation with VHTR when the price for natural gas is of the order of 8 US$/MMBtu or higher. An artist's view of what such a plant could look like is given in Fig. 11.

Most of the DOE-financed R&D on the VHTR is geared towards reducing technical uncertainties that impact licensing and involves industry, national laboratories and universities. Fuel kernels (UO_2 and UCO) were produced by Babcock & Wilcox (B&W) and coated at ORNL for irradiation and safety testing at INL. Subsequently, an industrial scale line for kernel production, coating, overcoating and compacting has been qualified at B&W. The qualification program performed so far demonstrates excellent fuel performance beyond design temperatures and burn-ups in the AGR-1 and AGR-2 irradiations as well as in safety tests. The novelty of the US program is that it goes beyond the pure evidence required for fuel qualification but puts emphasis on the full understanding of fission product transport mechanisms in fuel particles.

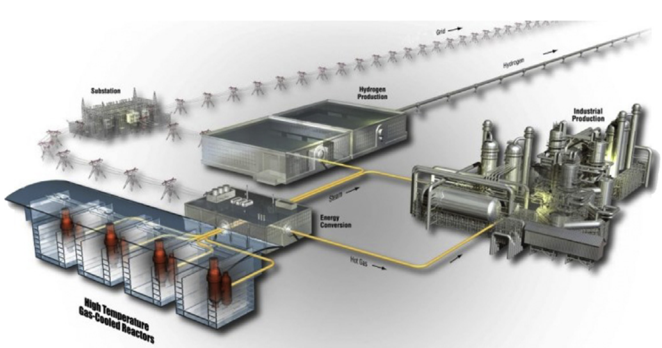

Fig. 11. Artist's view of a 4-pack modular VHTR for process heat, hydrogen production and electricity generation.

Additional research aims at understanding the stability of graphite at operating temperature under irradiation and with (thermo-)mechanical loads and at qualification of metallic alloys for structural materials to obtain the performance data needed to expand high temperature metals applications and to revise the associated design codes. Also in support of licensing, a complete set of codes is being developed, verified and validated in the areas of neutron physics, thermal-hydraulics and accident simulation. Additionally, experiments are conducted to validate safety-relevant modeling and simulation tools, for instance the High Temperature Test Facility at Oregon State University and the Natural Circulation Shutdown Heat Removal Test Facility at ANL. The work is coordinated with the US NRC to establish a licensing framework.

6.3. Japan

VHTR-related R&D in Japan is essentially performed by JAEA. The program consists of three elements, namely HTTR related tests, the development of innovative designs and hydrogen production technology (Kunitomi, 2013).

6.3.1. HTTR

After the restart of the reactor planned for early 2015, further tests are planned to evidence safety in accidental conditions at full power (loss of forced cooling and station blackout at 30% power) with the aim to convince the regulator and the public of the benign safety performance of this reactor type. A part of that work is performed within an OECD/NEA project with the USA, South Korea, Czech Republic, France, Germany, Hungary and Japan as partners.

6.3.2. Innovative HTR designs

This R&D encompasses the design of a Naturally Safe High Temperature Reactor (NSHTR) with demonstrable safety based on passive natural phenomena that would prevent radioactivity release even in worst case accidents. Related R&D aims at confirmation of a resulting low radioactivity inventory in the primary cooling circuit and relies on tests with the HTTR, e.g. simulation of a station black-out and control rod ejection. Experiments are planned aiming at the evaluation of oxidation of the SiC layer on coated fuel particles and the development of oxidation-resistant graphite (ex. through coating with SiC), both in response to an air or water ingress accident. A second innovation is the design of a Clean Burn High Temperature Reactor (CBHTR) to incinerate surplus plutonium from reprocessing of LWR spent fuel. This design would use fuel kernels made of PuO_2 in an inert matrix (yttria stabilized zirconia) to achieve a 95% Pu-239 incineration with consecutive direct disposal. Planned R&D on this subject includes fuel design, manufacture and quality control, irradiation and safety tests and the investigation of long-term behavior of such fuel in repository conditions. In collaboration with the Republic of Kazakhstan a Multi-purpose HTGR (MPHTR) is being designed with a power of 50 MWth. Applications include electricity production, district heating, and hydrogen production. The MPHTR includes the formerly developed GTHTR-300 series currently as a potential export product for Middle East countries.

6.3.3. Hydrogen production technology

The 2008 technology roadmap for nuclear hydrogen production envisions the introduction of commercial HTGR hydrogen production around 2030 and foresees by 2020 reliability demonstrations achievable in the HTTR and the associated systems dedicated to pre-industrial S–I cycle demonstrations. In this context, a new S–I test facility with a capacity of 200 l/h H_2 is under construction with startup scheduled for 2014. Operational feedback from this facility would enable further upscaling to a system coupled to the HTTR with an envisaged production of 1000 l/h H_2.

6.4. South Korea

The South Korean interest in High Temperature Reactors is driven by the country's dependence on fossil fuel imports, by the need for process heat in industry, by the large consumption of hydrogen in the petrochemical industry and by the prospect of performing iron ore reduction by hydrogen instead of coke which currently causes considerable CO_2 emissions from the steel making sector.

The South Korean long-term VHTR development plan consists of two major projects: the nuclear hydrogen key technologies development project and the nuclear hydrogen development and demonstration (NHDD) project. The former project focuses on development and validation of technologies required for the realization of a nuclear hydrogen system. This encompasses computational tools, high temperature experimental technology and hydrogen production processes. This project will continue until 2017. The goal of the NHDD project is to design and build a nuclear hydrogen demonstration system before 2030. Key technologies for VHTR and nuclear hydrogen are being developed according to the national R&D program. A helium loop for testing components was built, TRISO fuel fabrication was pursued, and fuel irradiation capability was acquired with an irradiation test in the HANARO reactor that started in July 2013. Preparations to acquire safety testing capability are underway. In 2013, a facility for lab-scale pressurized S–I hydrogen production (50 l/h) was started up.

A nuclear hydrogen alliance with industry has formed to develop cooperation plans under the NHDD project. In 2013, the Korean alliance has signed a memorandum of understanding with its US equivalent, the NGNP Industry Alliance.

A conceptual reactor design study was started in 2012 as a first collaboration between industry and government.

6.5. Europe

In Europe, a partnership of European nuclear industrial and research organizations for developing HTR technologies was established with the creation in 2000 of the (European) "HTR Technology Network" (HTR-TN). HTR-TN has played since then a prominent role in defining a strategy for European R&D on HTR and implementing this strategy in the form of a significant number of R&D projects with the European Commission as the funding authority. These projects were initially targeted to revive existing European experience on HTR design tools and technologies (fuel, materials, components, helium technology, coupling technologies, plutonium and minor actinide incineration etc.) first in a number of specific projects (e.g. on fuel, materials, safety and licensing), later in the form of the larger integrated technology development project RAPHAEL.

In 2011, HTR-TN was integrated in the Sustainable Nuclear Energy Technology Platform (SNETP) which gathers more than one-hundred players in nuclear technology across Europe. This platform defines strategies and proposes priorities for R&D, demonstration and deployment in nuclear technology, including in nuclear cogeneration of heat and power where HTR related work takes place.

This sets the stage for Euratom to bring consistent contributions to VHTR R&D projects in GIF and for approaching industrial sectors potentially interested in low-carbon process heat. The European projects are designed for compatibility with the GIF project structure and most of the deliverables can be disclosed to all GIF VHTR projects.

The most recent European contributions to GIF come from the following projects:

CARBOWASTE was the first project to investigate waste management for graphite moderated reactors and HTR fuel which is a so far little considered aspect. However, owing to the need for decommissioning of dozens of graphite moderated reactors with more than 250 000 t of irradiated graphite to tackle, Europe has a particular receptivity and responsibility with regard to this subject. Apart from finding solutions for legacy waste, this project is important for a possible deployment of VHTR in Europe insofar as a waste management strategy will probably have to be proposed as part of a future licensing application. In particular, the project has developed and tested several techniques at laboratory scale to decontaminate irradiated graphite in view of disposal or possible recycling, to drastically reduce fuel waste volumes and to enable recycling of nuclear material. CARBOWASTE was terminated in 2013 and a follow-on project is under discussion.

EUROPAIRS (finished in 2011) has successfully connected nuclear technologists with utilities, technical support organizations and a number of different end-users, e.g. from the (petro-)chemical, steel or fertilizer industry. The cooperation has enabled an improved understanding of end-user and utility requirements from a technical and economic perspective and enabled to improve the HTR development strategy in Europe. A strategic alliance was created between the key players in nuclear technology and from industrial end-users which would then become the Nuclear Cogeneration Industrial Initiative (NC2I). It has similar objectives as the NGNP Industry Alliance in the US, in particular to promote demonstration of nuclear cogeneration as a prerequisite for market deployment. The interface between nuclear plant and end-users was also given more attention as there were so far neglected constraints from a technical and licensing point of view. An R&D roadmap was developed towards demonstration of a nuclear cogeneration plant using a VHTR. Quite importantly, a market study and an economic assessment were performed in Europe which identified process steam below 600 °C as the biggest near-term opportunity with a current potential of approx. 87 GWth. As a result, most R&D was then oriented towards getting a medium-size HTR with a secondary steam cycle ready for licensing.

The required technology development is pursued in the *ARCHER* project which performs R&D in support of demonstration. Areas of work include system integration assessment of a nuclear cogeneration unit coupled to industrial processes, the analysis of safety and licensing aspects, R&D on fuel and fuel back-end, and material characterization in view of developing suitable design codes and standards. The ARCHER project will run until 2015 and has already produced a variety of solid results.

The *ADEL* project targets the development of cost-competitive, energy efficient and sustainable hydrogen production with intermediate temperature steam electrolysis (approx. 600 °C). Techniques are developed to enhance the performance and durability of electrolysis cells, and flow sheets are built to optimize the coupling between the energy source and the electrolyzer. Although ADEL focuses on the use of renewable energy, the consortium has agreed to provide certain deliverables to GIF.

In October 2013 a new small 2-year project was started to support the work of NC2I and to further elaborate a demonstration strategy. Amongst others, this project (*NC2I-R*) takes stock from earlier nuclear cogeneration experience in various countries, maps required infrastructures and competences, prepares for licensing and analyzes likely deployment scenarios. Its focus is, however, mainly to overcome non-technical hurdles in the innovation chain from R&D to market roll-out.

6.6. France

Since GIF-relevant R&D in France is now focusing on the development of a sodium fast reactor, it does no longer contribute VHTR specific R&D to GIF, but results from crosscutting activities with other systems. In the area of materials this includes characterization work on ferritic-martensitic and ODS steels as well as on composite materials such as C/C or SiC/SiC ceramics. France is participating with TRISO coated fuel particles in the shared irradiation test AGR-2 in the ATR reactor at INL and provides its results on high temperature electrolysis for hydrogen production.

As French companies and R&D organizations keep participating in European projects, further contributions on VHTR technology, graphite and fuel waste management and hydrogen production are channeled to GIF via Euratom.

6.7. Switzerland

Switzerland has decided to phase out nuclear power in the 2020s. However, especially crosscutting materials related research on innovative reactors is continued with emphasis on irradiation behavior of ODS steels and SiC/SiC composites. The work is coordinated and shared within the GIF VHTR Materials project. As Swiss R&D organizations keep participating in European projects, further contributions are channeled to GIF via Euratom.

6.8. IAEA, OECD and other countries

At United Nations level, the IAEA coordinates a number of technology projects related to gas-cooled reactors. Those are currently dealing with safety standards, core physics and thermal hydraulics, fuel, graphite and the related modeling.

The IAEA also performs technical-economic analyses and provides support for non-electric applications of nuclear power which are of interest for the VHTR, namely on seawater desalination, hydrogen production and other industrial process heat applications. The support is given in the form of technical meetings, conferences and courses. Furthermore, the IAEA runs the Advanced Reactors Information System (ARIS) which hosts a significant amount of information on HTR which is only rivaled by the information library of the World Nuclear Association. The efforts of GIF and the IAEA are coordinated in regular meetings.

The OECD not only provides the GIF Technical Secretariat and document management services, it also performs its own studies and organizes experts meetings on specific subjects. The most recent meeting was held together with the IAEA in April 2013 on Technical and Economic Assessment of Non-Electric Applications of Nuclear Energy.

Especially on conferences, several other countries and regions report on their activities. These range from academic work, e.g. in Mexico or Taiwan to bilateral projects (e.g. Japan–Kazakhstan) and fully-fledged feasibility studies, most recently from Saudi Arabia. The proceedings of the bi-annual HTR conference series provide a regular snapshot of current developments.

Finally, it is noticeable that two small start-ups are currently trying to bring pebble-bed HTR to a commercial state. One of them is X-energy in the US, the other Steenkampskraal Thorium Limited in South Africa. Both companies propose a small modular 100 MWth reactor for multipurpose steam generation in the near term and are in the fund raising stage to develop a basic design which would then allow them to enter a licensing process.

7. Open technical issues and future R&D priorities

In several of the GIF member countries an improved cooperation between future stakeholders in nuclear cogeneration using VHTR technology has started several years ago. These stakeholders comprise nuclear vendors, utilities, technical support organizations as the interface with regulators, and potential end-user industries which formed "Alliances" of mostly multi-nationally operating companies in the US, in South Korea and in Europe.

Industrial sectors concerned include the oil industry (upgrading of heavy oil, extraction & treatment of oil sands, production of synthetic fuels from coal, biomass or captured CO_2), as well as the chemical (plastics), fertilizer (hydrogen) and steel industries (hydrogen). Early dialogues and cooperation with national authorities, regulators and the public are sought.

It is the shared view of these alliances that the necessary next step towards market roll-out is an application-relevant demonstration in terms of licensability, safety, performance and cost. Because this low-carbon technology responds clearly to energy policies and societal issues in many countries such as emission reduction, energy independence, price stability, jobs, tax income and others, and because its first application involves economic risk, the alliances argue that this demonstration should be financially supported by the public, hence the proposal to form a public–private partnership.

The medium-term R&D focus has shifted to process steam generation requiring reactor outlet temperatures of up to 850 °C, whereas more ambitious applications such as thermo-chemical hydrogen production were identified as longer term. From this situation, priorities for future GIF R&D were derived and updated in the GIF Technology Roadmap Update (2013). These should continue to focus specifically on licensing and demonstration-relevant topics (cf. areas addressed in Section 5) and on system integration issues, i.e. how to couple a VHTR with end-user industries and how to integrate such combined energy systems in expected future energy mixes with more variable renewables.

Like many other "great ideas", the innovations related to the use of VHTR are only the first small step for the creation of value and are facing obstacles on the way to market roll-out. GIF countries have already invested very significant amounts on VHTR R&D, outstanding achievements could be reported, and the reasoning for this commitment over the last decade has become even clearer. But this investment would be lost if it was not followed by demonstration and deployment.

Therefore, in addition to performing the necessary R&D, the GIF VHTR members are preparing to critically analyze and resolve a number of often country-specific and not necessarily technical obstacles. Examples for these are incomplete understanding of how the VHTR fits a wider energy ecosystem, an industrial strategy, the identification of supporters and competitors, an appropriate business model and a market development strategy, management of intellectual property in international cooperation, difficulties in finding suitable financing options, timeliness, opportunities in communication or attractiveness for decision makers. A continued close link on these subjects with the alliances would be beneficial.

With all the technical evidence at hand, GIF takes the responsibility to carry the findings back from the R&D level to the political decision makers and ultimately to the taxpayer whose money was invested in the R&D. More than ever it is necessary that GIF keeps contributing its share to raise attention of the public, media, industry and politicians to the need to clean up not only the electricity generation sector but, and possibly even with higher priority, also industry and transport. The issues addressed by the VHTR are so crucial that they must not be exposed to technological fashions and political ups and downs.

7.1. System integration and assessment

A System Integration and Assessment project was under discussion in the past years but is not yet active in the GIF VHTR System. Nevertheless, most of the GIF VHTR members have performed design and system integration work, but the results were not shared through GIF. However, such a project which would go beyond generic issues in the areas of fuel, materials and hydrogen production would be beneficial to provide guidance and momentum for future R&D, demonstration and deployment. It would deal with the full reactor and the balance of plant, i.e. it would include electricity generation and end-user processes and their interfaces with the reactor.

Process-specific R&D gaps need to be filled to adapt the end-user and the nuclear heat source to each other with regard to temperatures, power levels, and operational pressures. Heating of chemical reactors by helium is a departure from current industrial practice and needs specific R&D and demonstration. The development of an intermediate heat exchanger, ducts, valves and associated heat transfer fluid are needed to provide process heat to end-users.

The viability of using nuclear process heat for producing hydrogen is more of a concern in extreme temperature conditions than it is in process steam scenarios and needs further study. Although tritium is now known to be much less of a problem than initially thought, any contamination of the product will have to be avoided. Development of heat exchangers, coolant gas ducts, and valves will be necessary for isolation of the nuclear island from the production facilities.

The VHTR balance-of-plant is determined by the specific application, which can be process heat, electricity production or cogeneration. A variety of process heat applications were studied by all GIF VHTR members to understand the technical needs of the specific process, to evaluate potential reactor and balance of plant configurations, and to provide an economic assessment of using a VHTR in the specific application.

In these process heat applications, all components have to be developed and qualified for their operating conditions and expected lifetime. Failure mechanisms such as creep, fretting, and ratcheting have to be studied in detail, precluded with design, and demonstrated in component tests. Specific components such as helical coil tube bundle steam generator, IHX, isolation valves, hot gas ducts with low heat loss, steam reformers, and process-related heat exchangers have to be developed for use in a modular VHTR, which mostly uses only one loop. Depending on the envisaged reactor size, this can lead to the need of larger components than formerly developed and a new design approach by modularisation of the component itself.

Steam generation options for electricity and/or process heat are technically ready. They combine the high efficiency of a VHTR and the maturity of steam turbines used in fossil power plants. This is a near term, low risk, large market and high performance option for the VHTR. Design, manufacturing, operation, in-service inspection of steam generators requires more efforts and feedback from previous operation experience. Supercritical water conditions could further increase the efficiency of a steam cycle VHTR while supercritical CO_2 power conversion systems may also deserve some attention.

A helium Brayton cycle requires approximately 250 K higher working fluid temperature for reaching the same efficiency as a steam Rankine cycle. Therefore, Brayton cycles are mainly of interest for long term VHTR options with significantly increased outlet temperature or when the use of steam is excluded. Some key components such as recuperator, helium turbine, and IHX would then require more R&D.

Some heat transfer fluids other than steam or helium could be envisaged to drive certain end-user processes. Of particular interest would be liquids e.g. molten salts because they would allow operation at low pressure. Circuit components would then need to be designed for such specific applications.

7.2. Safety and waste

In the eyes of the media and the public, nuclear technology is often associated with issues in the areas of safety and waste. Therefore, future R&D which reproduces further simple, robust, replicable, demonstrable evidence of a VHTR system's (including balance of plant) benign safety performance in worst case scenarios would be a considerable step forward.

Passive decay heat removal systems have been designed to facilitate operation of the VHTR, with a final goal of simple operation and transparent safety concepts. Experimental demonstration and validation of key features is underway with large in-vessel and ex-vessel experiments in the US. Over the next 5 years, these experiments are anticipated to evaluate depressurised conduction cooldown events in a VHTR and demonstrate the role of the reactor cavity cooling system in the passive safety response of the plant.

To convince regulators and the public, analysis and new simply understandable demonstration of the inherent safety features of the VHTR are needed which properly reflect all system design features. They could draw on previous demonstrations performed e.g. on AVR, HTR-10 and HTTR, and on new such tests as they are planned e.g. in the HTTR. HTTR and HTR-10 have been subjected previously to a series of operational transients to provide unique data on the response of a VHTR to upset conditions. This data will provide validation of reactor analysis tools.

Additional safety analysis is also necessary with regard to nuclear process heat applications in an industrial environment. Design basis and beyond design basis accident analyses for the VHTR need to include the presence of a process heat end-user. The licensing methodology for such combined plants is still country-specific and must be clarified with national regulators in view of possible simplification and standardization. Adequacy of existing models will need to be assessed and new models may need to be developed and validated.

The same holds for a credible waste management strategy: if GIF is able to demonstrate the feasibility of decontaminating and possibly recycling irradiated graphite and to achieve a considerable fuel waste reduction, it would proactively create the scientific substance to lessen public acceptance issues.

7.3. Cost reductions

Detailed economic studies have been performed for both electricity production and process heat applications by several GIF members and were shared informally. The US results suggest that modular VHTRs are competitive with new LWRs for electricity production. For process heat and co-generation applications, the VHTR can be competitive with conventional combined cycle gas turbine systems producing steam and electricity when the cost of natural gas is higher than 8 US$/MMBtu. Carbon taxes may reduce this threshold. Currently the cost of natural gas varies widely across the world. Thus, the economic viability depends largely on the financial and regulatory climate in each individual country. The inherent safety features of VHTR may benefit the economics index indirectly. Similar to certain other small and medium sized reactor concepts, the VHTR can also take credit for lower infrastructure requirements such as easier integration in weaker electricity grids, lower cooling requirements, and proximity to industrial sites and agglomerations.

After having established the technical feasibility of essential elements of a near-term VHTR, specific R&D could be devoted to making the system more attractive for investors, in other words make it cheaper (lower CAPEX), reduce the financial risk (e.g. by standardizing components, shortening construction and licensing), strengthen the effect of the “economy of replication” versus “economy of size”, and accelerate deployment and return on investment without compromising safety and performance. The claim that an *n*th-of-a-kind system will be *x*% cheaper than a first-of-a-kind is certainly correct and important, but it must be much better quantified and substantiated so that potentially critical areas can be improved and investors be convinced.

8. Conclusions

The unique capability of the VHTR to produce process heat above 600 °C makes it an efficient reactor type to displace fossil fuels in a number of various applications such as producing electricity, nonconventional hydrocarbon fuels from coal or biomass, and process heat for energy intensive industries (oil refining, oil sand recovery, petro-chemistry, chemistry, steelmaking…). Several market studies confirmed the potential for VHTR to be used in such applications and the economic boundary conditions (e.g. price of natural gas, CO_2 tax) for market deployment have become clearer. The inherent safety characteristics of the VHTR are a precious asset for it to become a strong response to today’s concerns of nuclear safety, energy security and climate change.

Current research programs within GIF and specific national programs address primarily issues related to developments, licensing, demonstration and deployment. In particular, the multinational cooperation within GIF allows sharing efforts to advance VHTR technologies and to accelerate development in view of licensing and deployment. Furthermore, both experimental reactors in operation in Japan (HTTR) and in China (HTR-10) offer unique opportunities to qualify precursor VHTR technologies and design codes.

This paper has provided an update on recent progress made by GIF VHTR R&D, it has placed it in the wider context of national programs and underlined the added value of cooperation within GIF. Possible orientations of future R&D were outlined beyond those activities which are already underway. These include system integration and assessment, nuclear safety analysis and demonstration, waste minimization and steps to make the economics of this technology more attractive to investors. Whether and when this R&D can be performed is subject to priorities and annual budget cycles in the GIF VHTR member countries.

The next hurdle in VHTR development is being taken by China with the ongoing construction of the commercial HTR-PM reactor. Japan will perform further safety demonstrations on the HTTR. Both are very valuable steps towards deployment of nuclear cogeneration of process heat and electricity and could be the basis for further input to GIF.

Although very substantial results were already obtained by the signatories of the GIF VHTR system, funding opportunities for a prototype coupled to an end-user process will have to be found soon to capitalize on previous investments. Several such international initiatives are on their way and are decisive for the future of VHTR R&D within GIF.

References

Angulo, C., et al., 2012. EUROPAIRS: the European project on coupling of high temperature reactors with industrial processes. Nucl. Eng. Des. 251, 30–37.
Baumer, R., Kalinowski, I., 1991. THTR commissioning and operating experience. Energy 16, 59–70.
Beck, J.M., Garcia, C.B., Pincock, L.F., 2010. High Temperature Gas-Cooled Reactors Lessons Learned Applicable to the Next Generation Nuclear Plant (INL/EXT-10-19329). Idaho National Laboratory, Idaho Falls, ID.
Bredimas, A., 2012. Results of a European industrial heat market analysis as a pre-requisite to evaluating the HTR market in Europe and elsewhere. In: Proc. HTR 2012, Tokyo, Japan, October 28–November 1, 2012.
Energy Development Opportunities for Wyoming (INL report, INL/EXT-12-26732), November 2012.
GIF Technology Roadmap Update 2013. Final Draft, 31.10.2013.
Harth, R., Jansing, W., Teubner, H., 1990. Experience gained from the EVA II and KVK operation. Nucl. Eng. Des. 121, 173–182.
Hochtemperaturreaktor-Modul-Kraftwerksanlage (Kurzbeschreibung), November 1988. Siemens/Interatom, Germany.
Konefal, J., Rackiewicz, D., May 2008. Survey of HTGR Process Energy Applications (MPR Associates Report MPR-3181).
Kunitomi, K., March 5, 2013. Status of HTTR project in JAEA. In: TWGGCR Meeting at IAEA.
Kunitomi, K., Katanishi, S., Takada, S., Takizuka, T., Yan, X., 2004. Japan’s future HTR—the GTHTR300. Nucl. Eng. Des. 233, 309–327.
LaBar, M.P., 2002. The gas turbine-modular helium reactor: a promising option for near-term deployment. Gen. Atom. GA-A23952.
Lommers, L.J., Shahrokhi, F., Mayer III, J.A., Southworth, F.H., 2012. AREVA HTR concept for near-term deployment. Nucl. Eng. Des. 251, 292–296.
Matzner, D., 2008. The pebble bed modular reactor. In: Letcher, Trevor M. (Ed.), Future Energy. Elsevier, Oxford (Chapter 14).
Neef, J., Weisbrodt, I., 1979. Coal gasification with heat from high temperature reactors: objectives and status of the project “Prototype Plant for Nuclear Process Heat (PNP)”. Nucl. Eng. Des. 54, 157–174.
Pohl, P., 2008. IRPhE/AVR, High Temperature Reactor Experience, Archival Documentation (OECD/NEA, NEA-1739/02). https://www.oecd-nea.org/tools/abstract/detail/nea-1739.
Price, M.S.T., 2012. The Dragon project: origins, achievements and legacies. Nucl. Eng. Des. 251, 60–68.
Reutler, H., Lohnert, G.H., 1984. Advantages of going modular in HTRs. Nucl. Eng. Des. 78, 129–136.
Schulten, R., 1976. Nukleare Prozeßwärme. Chem. Ing. Tech. 48, 375–380.
Shropshire, D., 4–5 April 2013. Integration challenges for nuclear cogeneration coupled to renewable energy systems. In: Proc. Joint NEA/IAEA Expert Workshop on the Technical and Economic Assessment of Non-electric Applications of Nuclear Energy (NUCOGEN). OECD, Paris, France.
Styring, P., Jansen, D., de Coninck, H., Reith, H., Armstrong, K., July 2011. Carbon Capture and Utilisation in the Green Economy, Using CO_2 to Manufacture Fuel, Chemicals and Materials. The Centre for Low Carbon Futures.
Thomas, S., May 2011. The pebble bed modular reactor: an obituary. Energy Policy 39 (Issue 5), 2431–2440.
Uranium 2011, 2012. Resources, Production and Demand, A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency. OECD, Paris.
Verfondern, K., 2007a. Survey on 20 years of R&D on nuclear process heat applications in Germany. In: IAEA Proceedings IAEA-CN-152-16, Intl. Conf. on Non-electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and Other Industrial Applications, Oarai, Japan, 16–19 April 2007.
Verfondern, K., 2007b. Potential for nuclear process heat application. In: IAEA Proceedings IAEA-CN-152-59, Intl. Conf. on Non-electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and Other Industrial Applications, Oarai, Japan, 16–19 April 2007.
Wu, Z., Lin, D., Zhong, D., 2002. The design features of the HTR-10. Nucl. Eng. Des. 218, 25–32.
Yan, X.L., Hino, R., 2011. Nuclear Hydrogen Production Handbook. CRC Press, ISBN 978-1-4398-1083-5.
Yujie, Dong, 2012. China’s activities in HTGRs HTR-10 and HTR-PM. In: IAEA Course on High Temperature Gas Cooled Reactor Technology, Beijing, China, 22–26 October 2012.
Zhang, Z., Wu, Z., Sun, Y., Li, F., 2006. Design aspects of the Chinese modular high temperature gas-cooled reactor HTR-PM. Nucl. Eng. Des. 236, 485–490.
Zhang, Z., Wu, Z., Wang, D., et al., 2009. Current status and technical description of the Chinese 2 × 250 MWth HTR-PM demonstration plant. Nucl. Eng. Des. 239, 1212–1219.

Glossary

AGR: advanced gas-cooled reactor
ASME: American Society of Mechanical Engineers
AVR: Arbeitsgemeinschaft Versuchsreaktor
CAPEX: capital expenditure
CEA: French Atomic Energy Commission
CHP: combined heat and power
FP6, FP7: European 6th, 7th European R&D Framework Programme
GIF: Generation IV International Forum
GT-MHR: gas turbine modular helium-cooled reactor
HTGR: high temperature gas-cooled reactor
HTR: high temperature reactor

HTR-10: 10 MW high temperature reactor
HTR-PM: high temperature reactor – pebble-bed module
HTR-TN: high temperature reactor technology network
HTSE: high temperature steam electrolysis for hydrogen production
HTTR: high temperature engineering test reactor
HWR: heavy water reactor
IHX: intermediate heat eXchanger
INET: Institute of Nuclear and New Energy Technology (Tsinghua University, Beijing)
INL: Idaho National Laboratory
JAEA: Japan Atomic Energy Agency
KAERI: Korea Atomic Energy Research Institute
LANL: Los Alamos National Laboratory
LCOE: levelized cost of electricity (or energy)
LWR: light water reactor
MHTGR: modular high temperature gas-cooled reactor
MWe: megawatt electric
MWth: megawatt thermal
NGNP: Next Generation Nuclear Plant
NHDD: nuclear hydrogen development and demonstration
OPEX: operating expenditures
ORNL: Oak Ridge National Laboratory
PBMR: pebble bed modular reactor
R&D: research and development
S–I: sulfur–iodine thermochemical process for hydrogen production
SNETP: European sustainable nuclear energy technology platform
SNL: Sandia National Laboratory
SFBR: sodium-cooled fast breeder reactor
THTR: thorium high temperature reactor
TRISO: tri-structural isotropic fuel
US-DOE: US Department of Energy
US NRC: US Nuclear Regulatory Commission
VHTR: very high temperature reactor